J/ψ suppression measurements by the PHENIX experiment at RHIC

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PHENIX

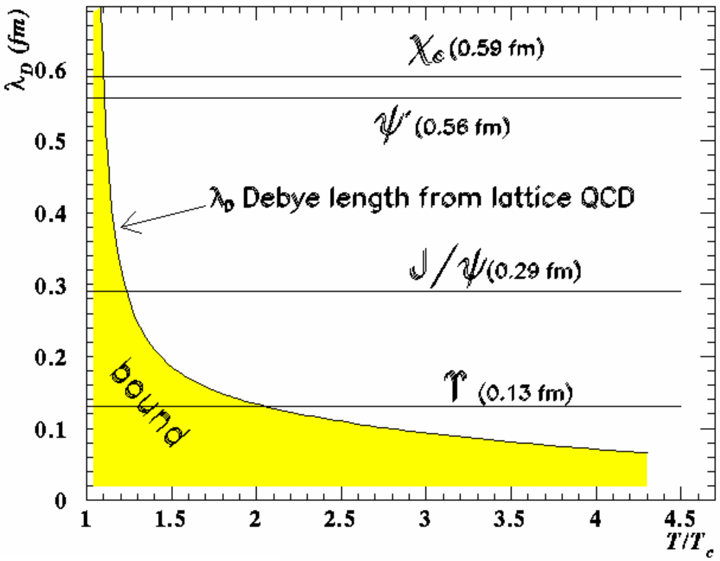
Physics motivations

- QCD phase diagram
  - QCD is only sector of SM where collective non equilibrium phenomena can be studied theoretically and experimentally
  - Lattice QCD predicts that, at high temperature T, and baryonic chemical potential μ_b, deconfinement and chiral symmetry restoration take place.
  - Such a state is called Quark Gluon Plasma (QGP)
- Heavy ion collisions (HICs)
  - It's possible to explore points far from the DIS region (T=0) in the L-QCD phase space through heavy ion collisions.
  - This is done by varying the energy and centrality of collisions as well as mass of colliding ions.
- Probing the medium
  - One of the promising probes to study deconfinement and QGP formation in HICs is the suppression of quarkonia, in particular J/ψ.

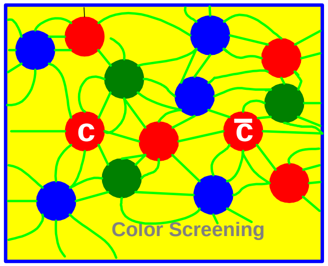
Screening in deconfined medium

- Debye screening
  - QCD screening length λ_D in deconfined medium decreases with temperature
  - Quarkonia "melt" when their binding distance becomes bigger than screening length

F. Karsch et al. (Nucl. Phys. A698(2002) 199c; hep-lat/0106019)



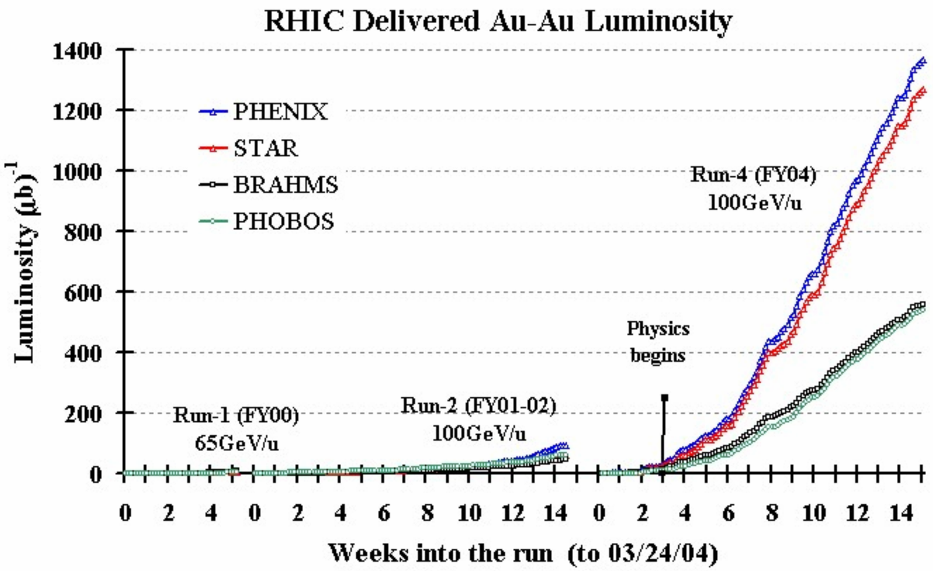
state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

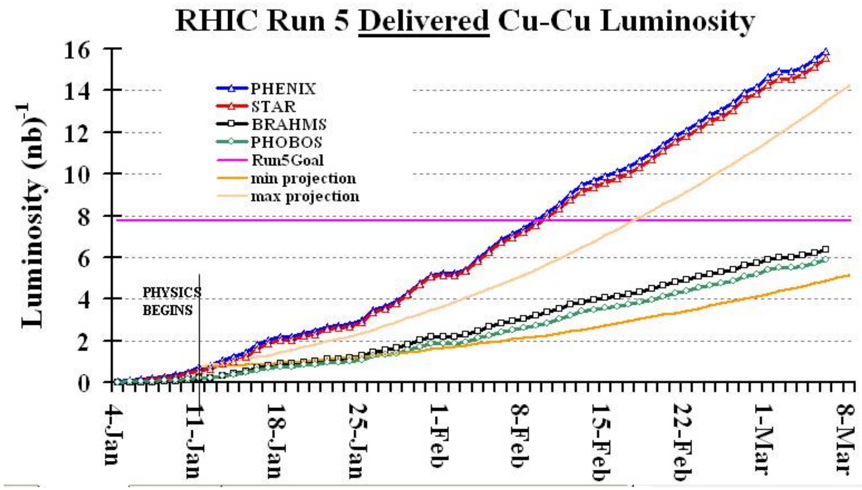


- Binding distance depends on quarkonium state
- "Melting" in QGP occurs at different temperatures

RHIC

- HI and polarized proton colliding machine
  - Operates with CM energy per nucleon in wide range
    - 200GeV & 500GeV in p+p
    - 22.5GeV & 200GeV in Cu+Cu
    - 62GeV & 200GeV in Au+Au
    - 200GeV in d+Au



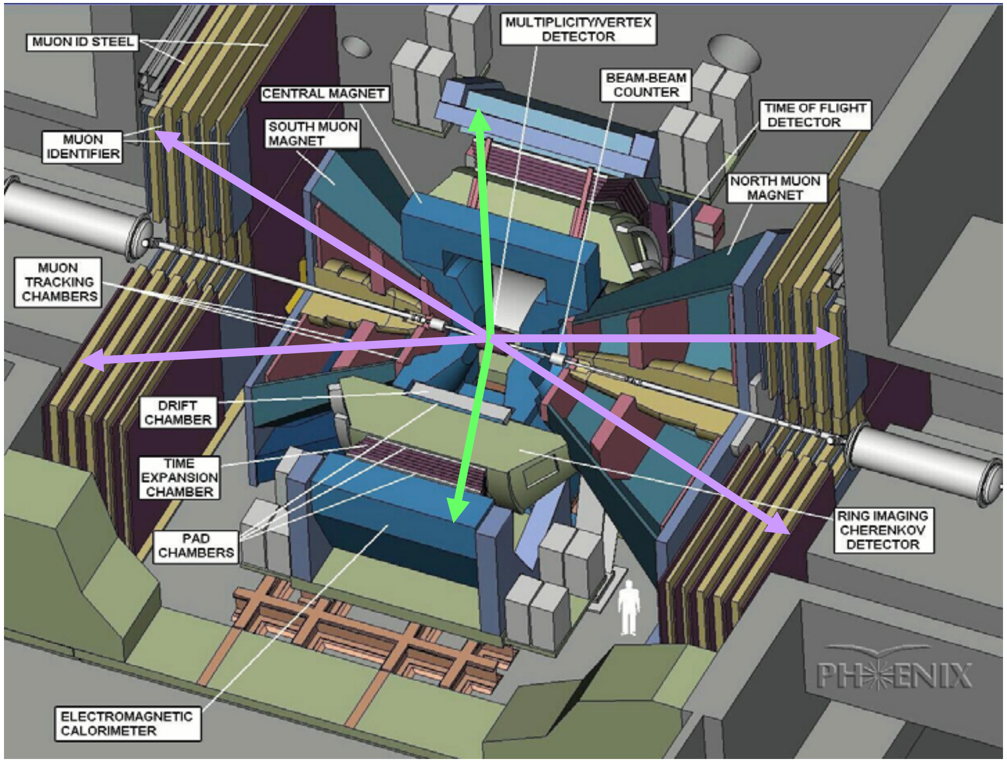


PHENIX J/ψ cross section measurements

Central Arms:

Hadrons, photons, electrons

- $J/\psi \rightarrow e^+e^-$
- $|\eta|<0.35$
- $p_e > 0.2$ GeV/c
- $\Delta\phi = \pi$ (2 arms x $\pi/2$)



Forward rapidity Arms:

Muons

- $J/\psi \rightarrow \mu^+\mu^-$
- $1.2<|\eta|<2.2$
- $p_\mu > 1$ GeV/c
- $\Delta\phi = 2\pi$

Global detectors

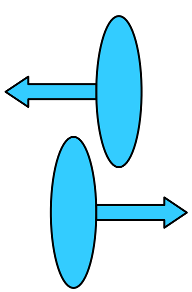
Beam-Beam Counter (BBC)

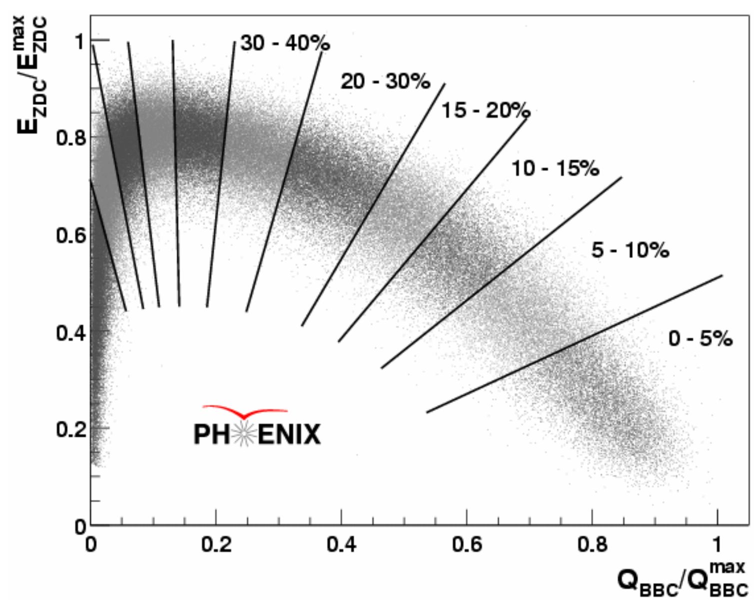
Zero Degree Calorimeter (ZDC)

Centrality classes

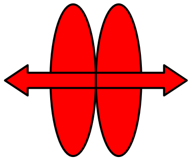
- Dividing total cross section according to centrality
  - Use BBC charge vs. ZDC energy
  - N_{coll} : number of binary inelastic N–N collisions
  - N_{part} : number of nucleons that undergo inelastic collisions
  - Glauber model + detector response simulation => $\langle N_{part} \rangle$ & $\langle N_{coll} \rangle$

Most peripheral
80 – 92.2%
$\langle N_{part} \rangle = 6.3 \pm 1.2$
$\langle N_{coll} \rangle = 4.9 \pm 1.2$



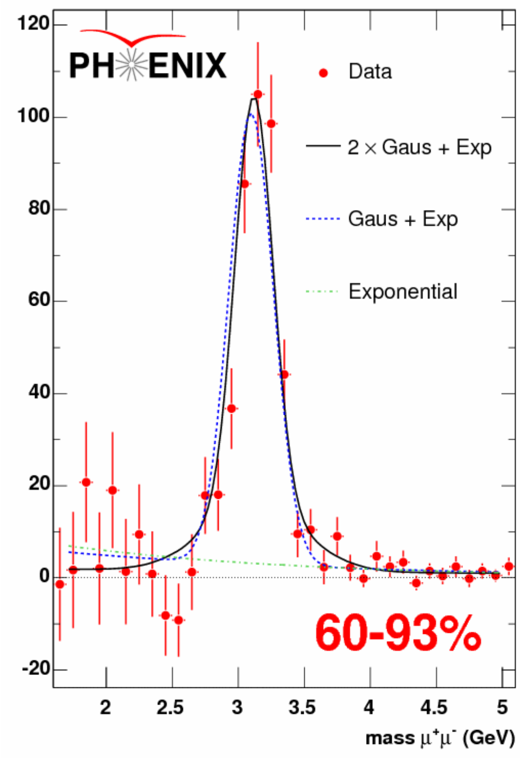


Most central
0 – 5 %
$\langle N_{part} \rangle = 351.4 \pm 2.9$
$\langle N_{coll} \rangle = 1065 \pm 105$

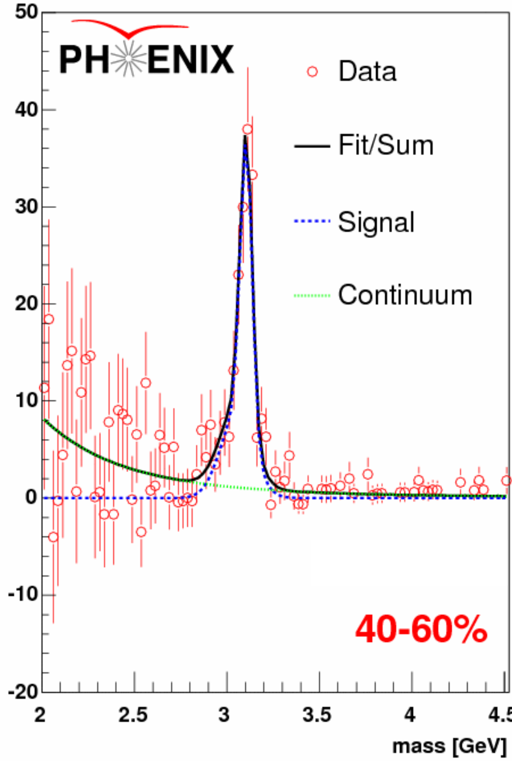


Signal extraction

- Invariant mass spectra of $\mu^+\mu^-$ and e^+e^- (B ~ 6% each)
- Combinatorial background subtracted by event mixing
- Fitted with:
  - Gaussians for the mass peak
  - Exponentials for physical background (heavy flavor decay and/or Drell-Yan)
  - Average value of various fits used as J/ψ count
  - Dispersion is included in systematic errors.



$J/\psi \rightarrow \mu^+\mu^-$



$J/\psi \rightarrow e^+e^-$

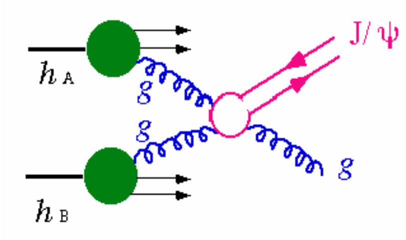
PHENIX J/ψ measurements summary

Run	Species	$\sqrt{s_{NN}}$[GeV]	∫Ldt	J/ψ counts (|y|<0.35)	J/ψ counts (1.2<|y|<2.5)	Reference
1	Au+Au	130	1μb-1			
2	Au+Au	200	$24\mu b^{-1}$	13		
	p+p	200	$0.15pb^{-1}$	46	65	PRC69, 014901(2004)
3	d+Au	200	$2.74nb^{-1}$	364	1186	PRL92, 051802(2004)
	p+p	200	$0.35pb^{-1}$	130	448	PRL96, 012304 (2006)
4	Au+Au	200	$241\mu b^{-1}$	1000	4449	nucl-ex/0611020
	Au+Au	63	$9\mu b^{-1}$			
	p+p	200	$350nb^{-1}$			
5	Cu+Cu	200	$3nb^{-1}$	2300	9000	(prel.)nucl-ex/0510051
	Cu+Cu	62	$0.19\mu b^{-1}$		146	
	Cu+Cu	22.5	$2.7\mu b^{-1}$			
	p+p	200	$3.8pb^{-1}$	1500	8005	hep-ex/0611020
6	p+p	200	$10.7pb^{-1}$			
	p+p	62	$0.1pb^{-1}$			
7	Au+Au	200	4x run 4?			

Running

Contributions to J/ψ cross-section in HICs

- Creation (at RHIC energies)
  - Directly in gluon fusions (gg → J/ψ)
    - Very early in nucleon-nucleon hard scatterings
  - Feed down from excited states of charmonia, multiple measurements
    - Example HERA-B : (χ_c → J/ψX) ~ 21±5% and (ψ' → J/ψX) ~ 7±0.4% (*)



- Gluon shadowing : modification of PDFs in nuclei
- Suppression
  - Absorption by receding fragments from initial heavy ions (J/ψ+N→X)
  - Interaction with fast moving gluons (J/ψ+g→X)
  - Dissociation by eventual QGP
- Enhancement
  - Possible recombination from <u>uncorrelated</u> c and $\bar{c}$ quarks

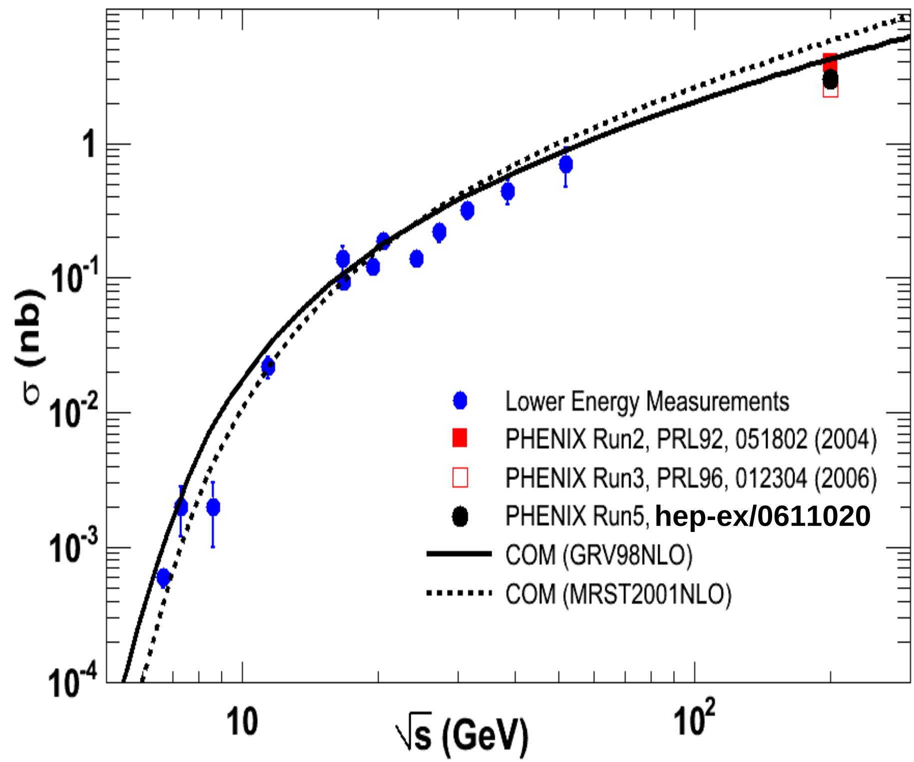
(*) Abt *et al.* Eur. Phys. J. C49 (2007) 545–558

J/ψ measurements in p+p collisions (1/2)

- Why J/ψ in p+p?
  - Heavy Ion collision yields are normalized by p+p collision yields

$$R_{AB}(y,p_t)=\frac{d^2N_{AB}/dydp_t}{<N_{coll}>\times d^2N_{pp}/dydp_t}$$

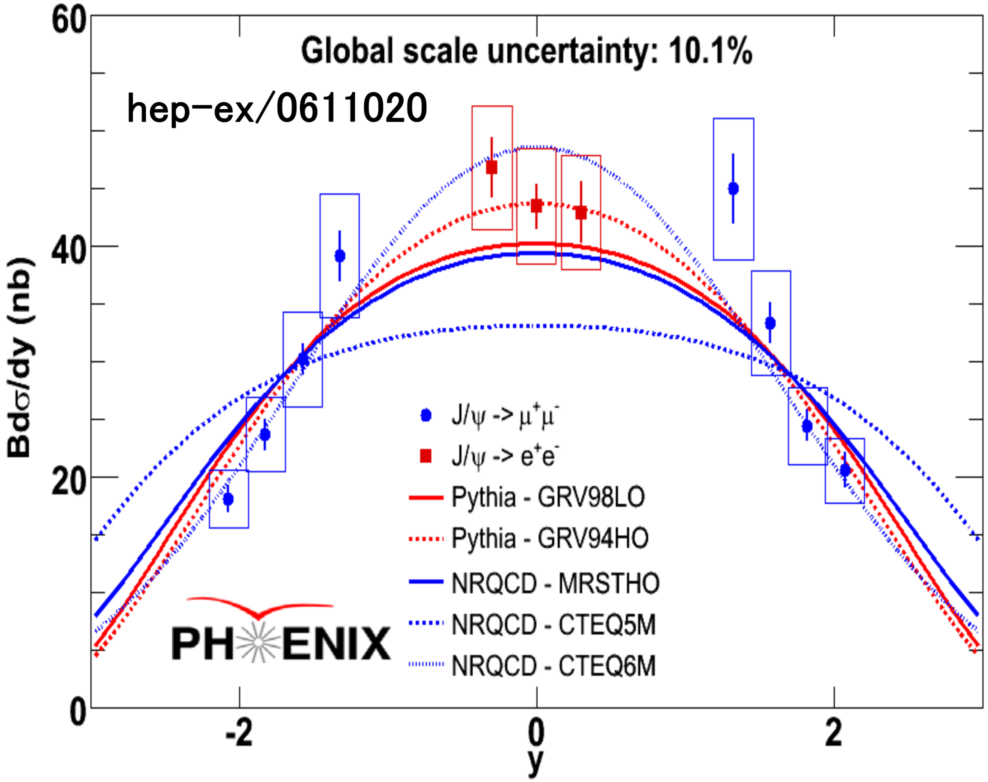
  - Clarify poorly understood J/ψ production mechanism (CSM/COM?)
  - Initial & final state absorptions (cold nuclear matter, gluon) depend on the J/ψ formation mechanism

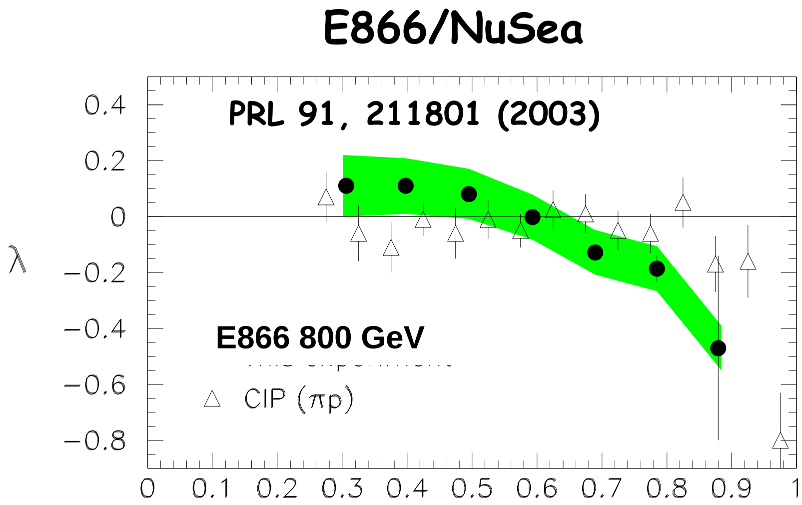


Total cross section fits to PYTHIA NLO

$$BR\cdot\sigma_{tot} = 178 \pm 3^{stat} \pm 53^{sys} \pm 18^{norm}\ \mathrm{nb}$$

J/ψ measurements in p+p collisions (2/2)





$x_F = x_1 - x_2$

$$d\sigma / d\cos\theta = A(1+\lambda\cos^2\theta)$$

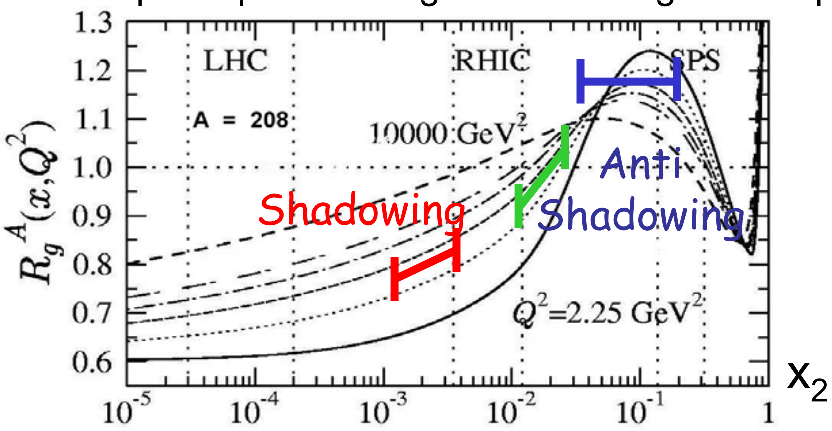
λ = +1 (transverse)
= −1 (longitudinal)

- Observation :
  - No model fits absolute cross section, rapidity distribution (RHIC), and polarization (example: E866) simultaneously

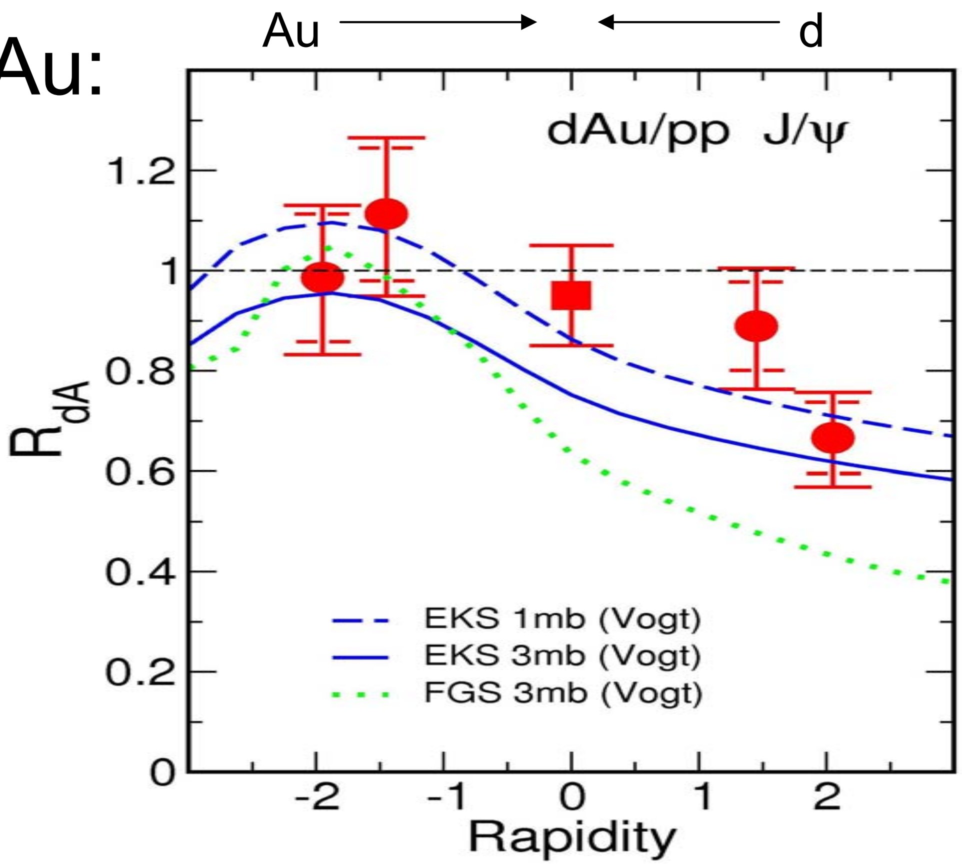
Cold nuclear matter (CNM) effects

- J/ψ suppression in d+Au:
  - PRL, 96, 012304 (2006)
  - Modest shadowing
    - EKS(*) favored
  - Weak nuclear absorption
    - $\sigma_{(J/\psi+N\rightarrow X)}$ ~ 1-3mb

Example of prediction: gluons in Pb / gluons in p



X_2 : Momentum fraction in nucleus



<Y>	<x2>
-1.7	0.09
0	0.02
1.7	0.003

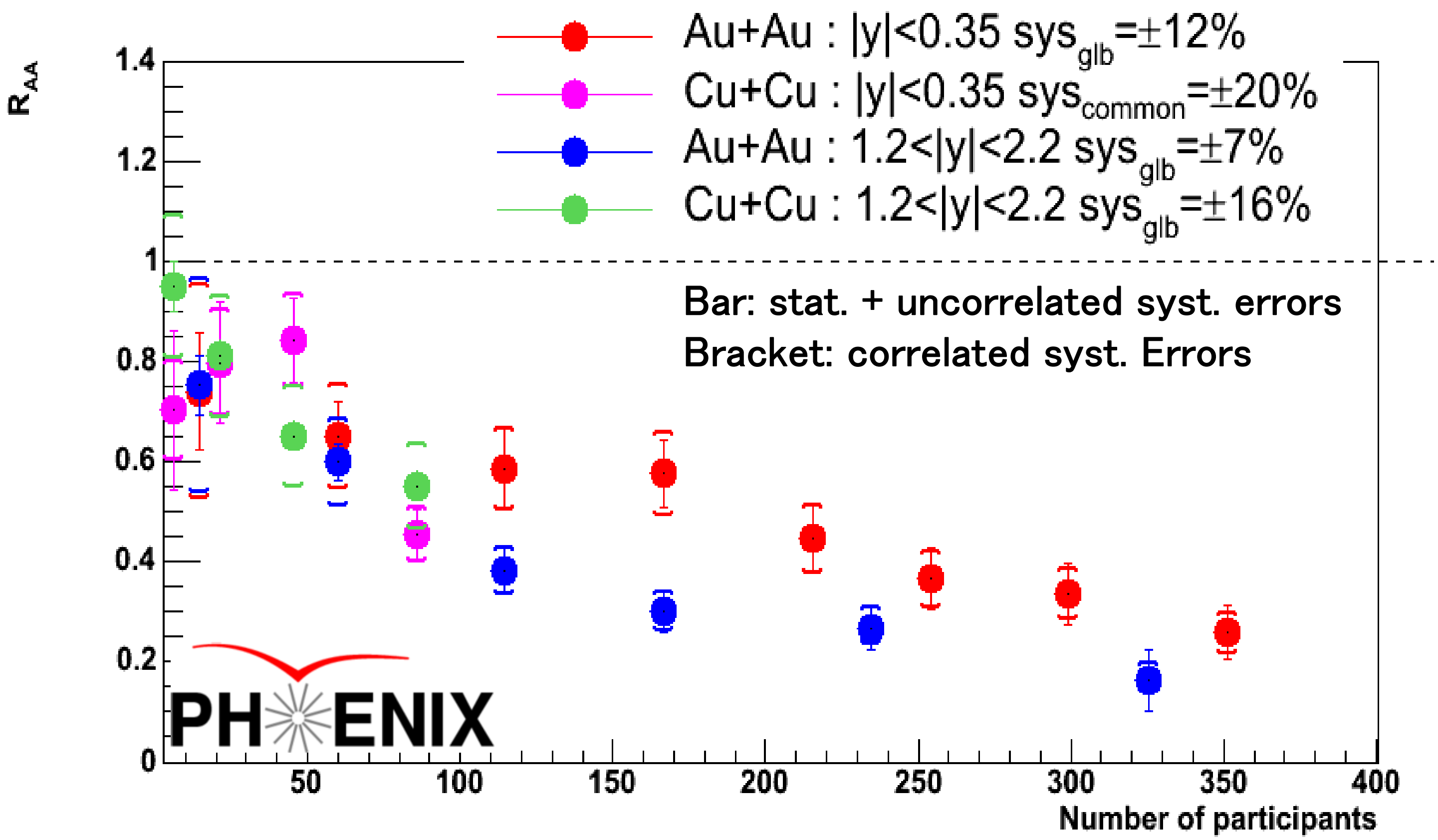
Effective x_2 vs. y at $\sqrt{s}$ = 200GeV, Δy=0

(*) Eskola, Kolhinen, Salgado Eur. Phys. J. C9 (1999) 61

Au+Au and Cu+Cu collisions

Au+Au final (nucl-ex/0611020)
Cu+Cu prelim (nucl-ex/0510051)

- Summary plot :
  - J/ψ suppression measurements in HICs



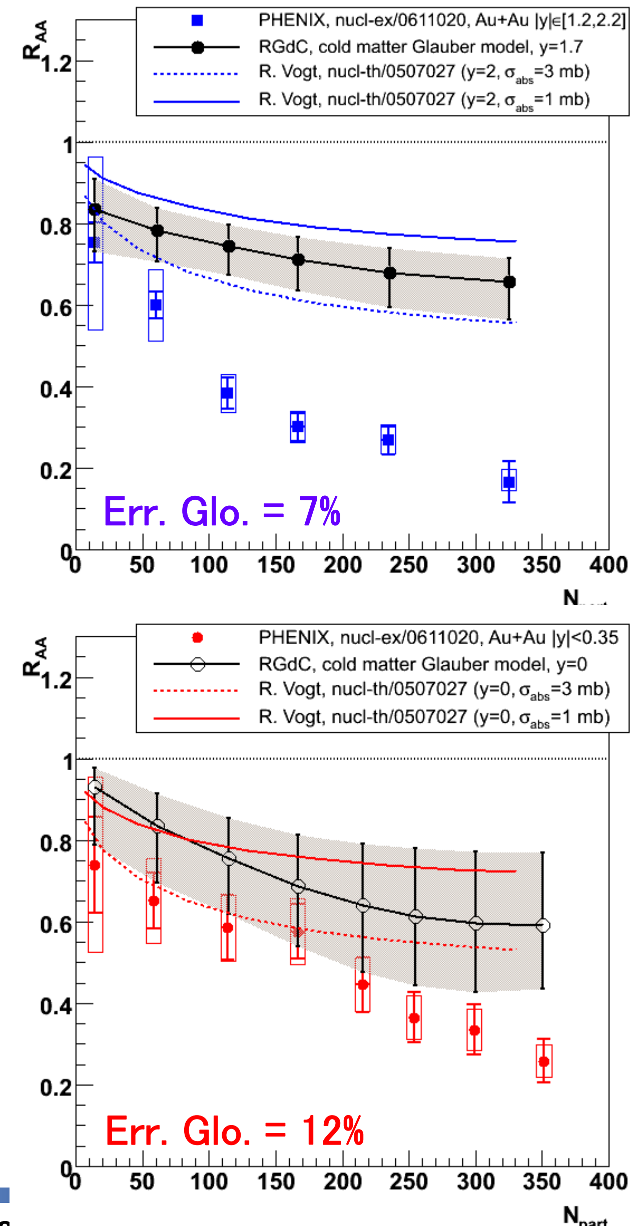
Suppression in most central Au+Au goes down to ~ 0.2

Comparison with extrapolations from d+Au

- Two calculations shown
  - CNM effects model based on 1–3mb absorption and shadowing. (*)
  - Glauber model + rapidity symmetrization of d+Au points (**)
    - $R_{AA}(\pm y) = R_{dA}(-y) \times R_{dA}(+y)$
- Suppression much higher than accountable by CNM effects
- Not possible with Cu+Cu
  - No d+Cu/p+Cu run

(*) R. Vogt, Acta Phys. Hung. A25 (2006) 97–103

(**) R. Granier de Cassagnac, hep-ph/0701222

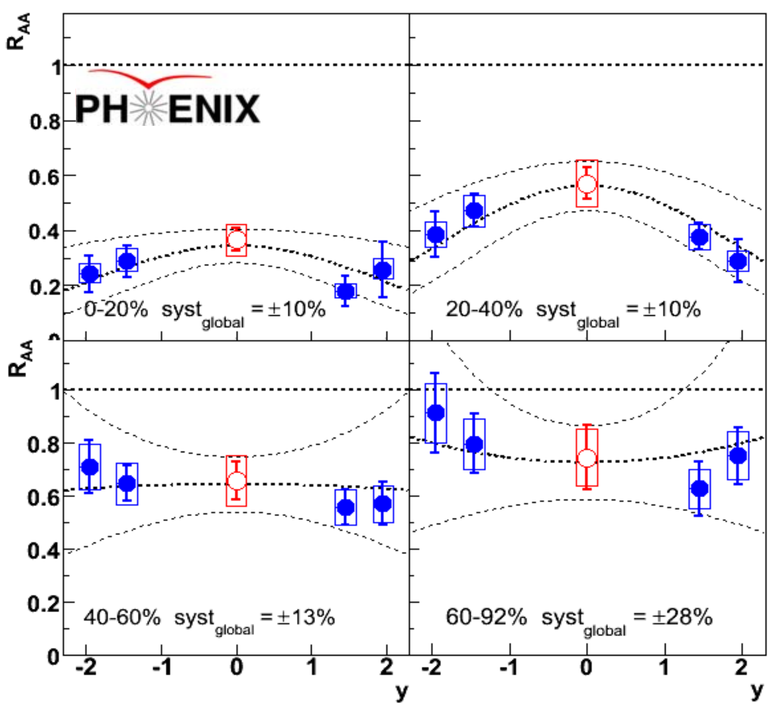


Bar : stat. + uncorrelated syst. errors

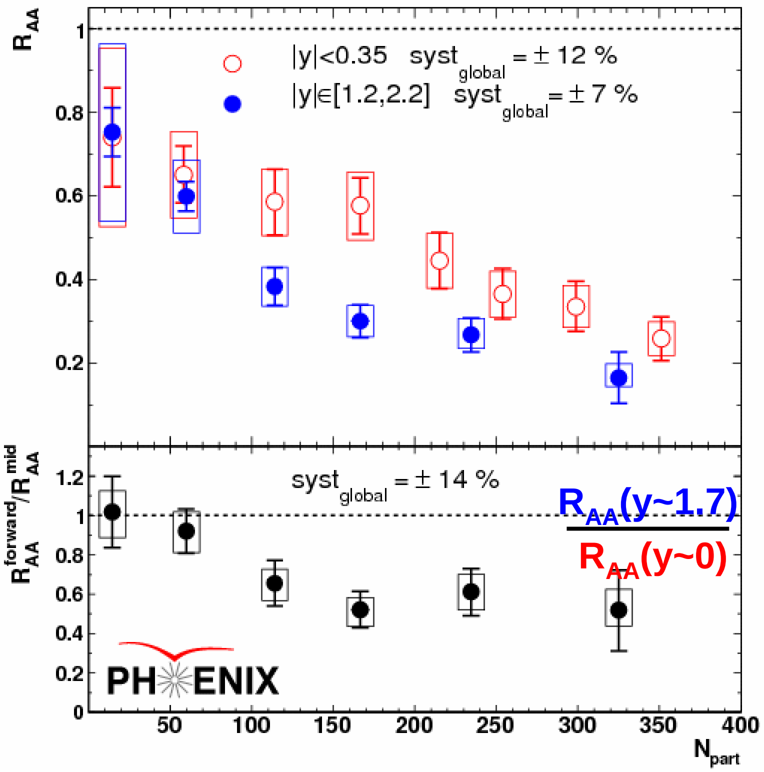
Box : correlated syst. errors

Rapidity dependence of suppression

- R_{AA} vs. rapidity for different centrality classes
  - Distribution gets narrower with increasing centrality
  - Challenge to most "local density" based models



Dashed lines : Gaussian fits.
Dotted lines : ± 1 σ variation of fit pars.



Bar : stat. + uncorrelated syst. errors
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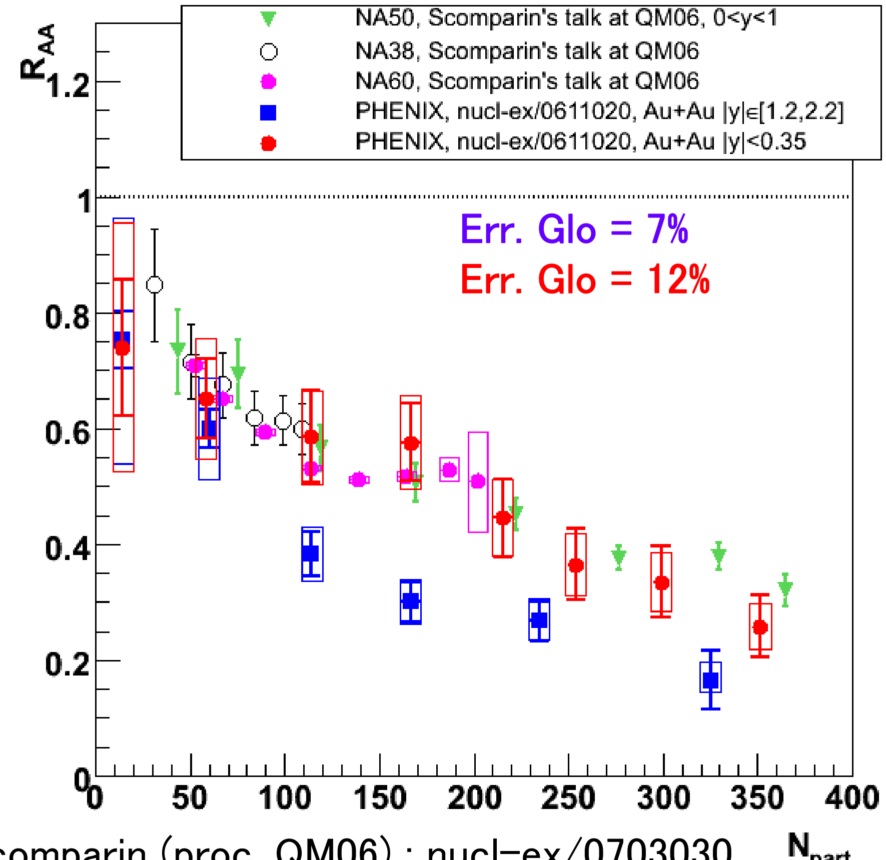
Direct comparison to SPS

- J/ψ were also measured in HICs at SPS
  - S+U (NA38), Pb+Pb (NA50) and In+In (NA60), fixed target ($\sqrt{s_{NN}} \sim 20$GeV)
- Comparing RHIC and SPS is delicate
  - Factoring out CNM effects (not same at SPS/RHIC)
- R_{AA} (y~0) ~ R_{AA} (SPS)
  - Not what's expected from $\sqrt{s_{NN,SPS}} < \sqrt{s_{NN,RHIC}}$
  - Rapidity ranges not same $0 < y_{sps} < 1$
  - Big error bars on RHIC data points
  - ~10% normalization error at SPS



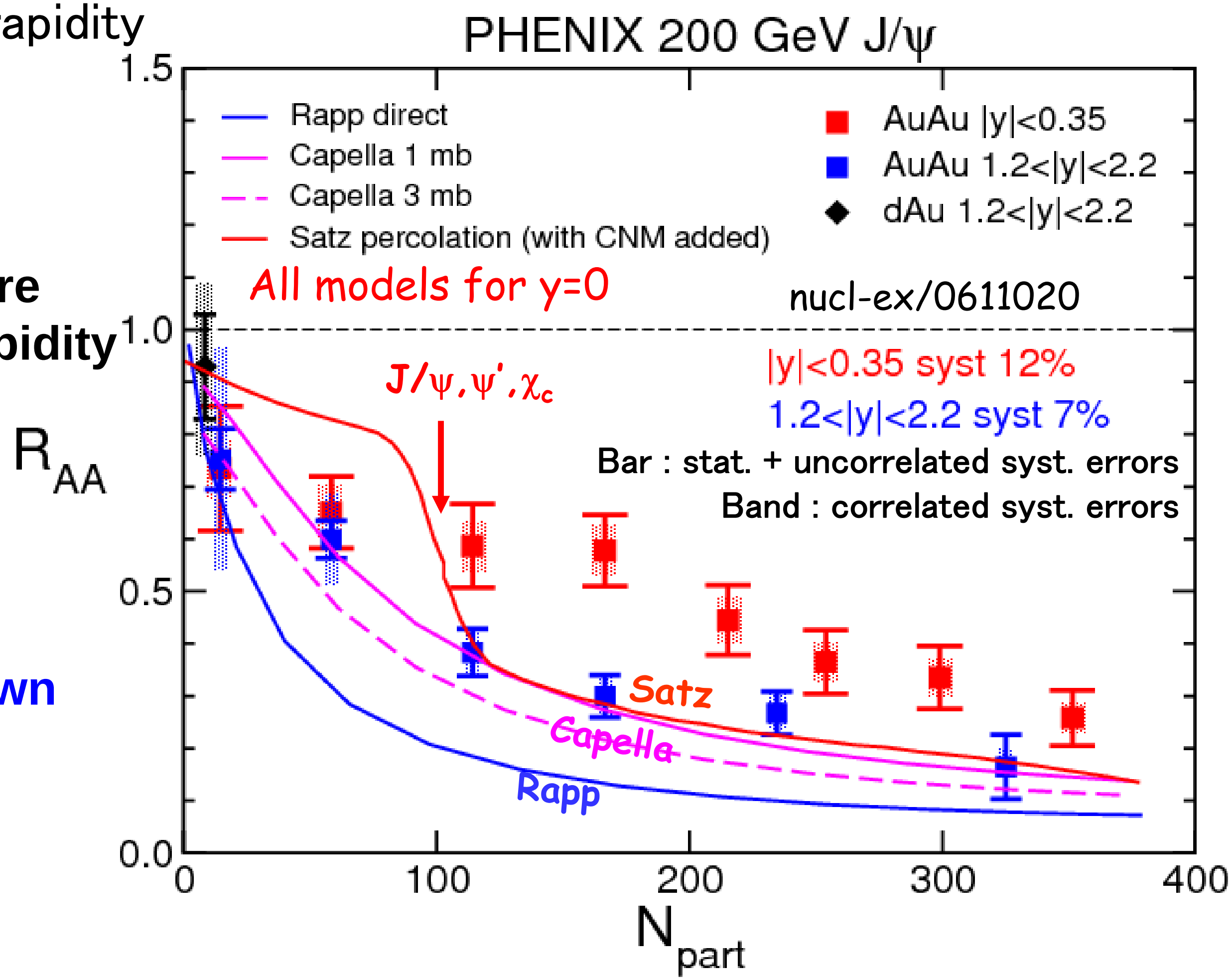
Scomparin (proc. QM06) : nucl−ex/0703030

Indirect comparisons to SPS

- Test with RHIC data models that worked at SPS
  - Most models are strongly challenged by the rapidity trend, and less suppression at mid rapidity

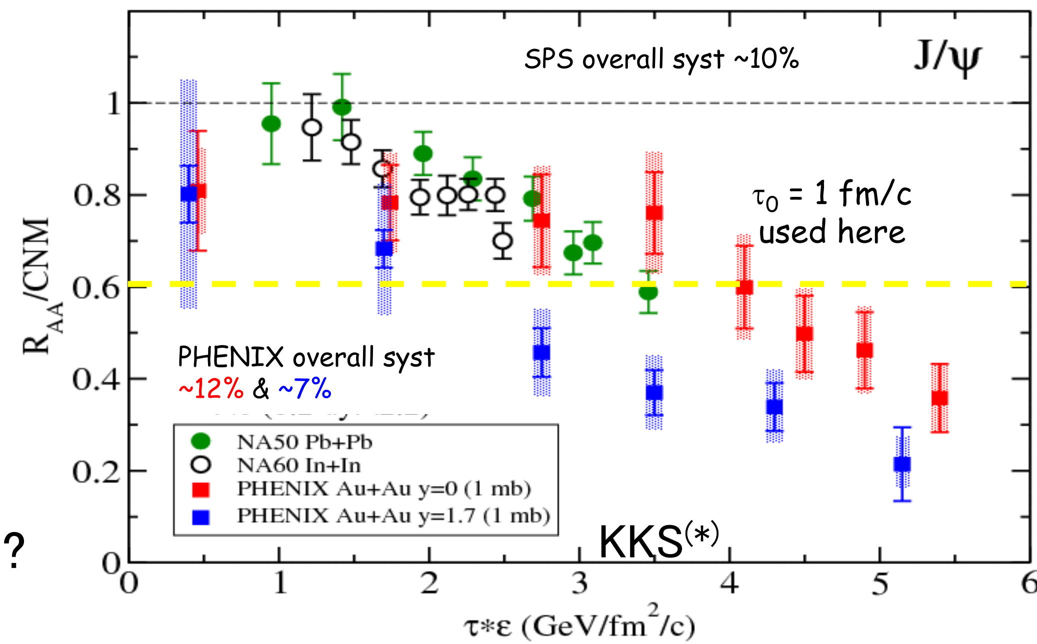
All calculations shown here give predictions at mid rapidity

- **Digal, Fortunato, Satz**
  - **hep-ph/0310354**
- **Capella, Ferreiro**
  - **hep-ph/0505032**
- **Grandchamp, Rapp, Brown**
  - **hep-ph/0306077**



Testing sequential melting

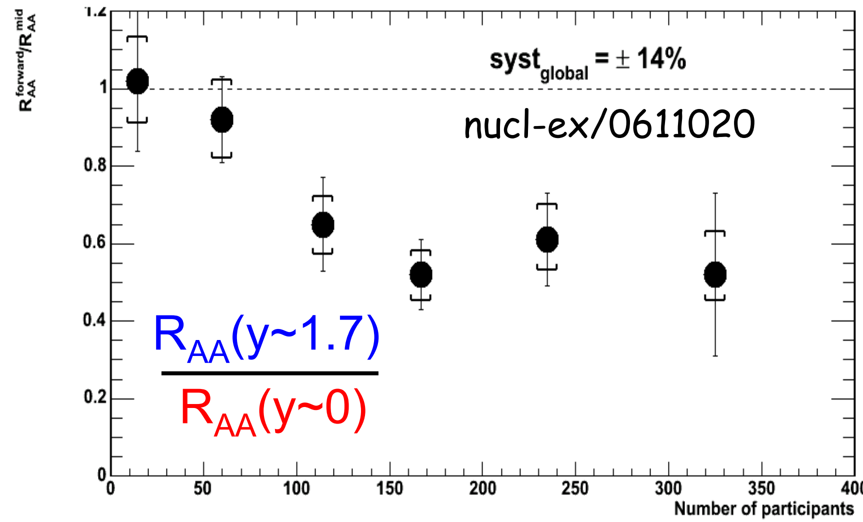
- Latest L-QCD results suggest :
  - No J/ψ suppression for $T<1.5T_c$ ($\gtrsim 10\text{GeV/fm}^3$) complete only $T>2.5T_c$
  - ψ' and χ_c start melting at $1.1T_c$ (possibly at RHIC)
  - Is suppression seen at RHIC & SPS only on feed down part?
- Survival probability
  - R_{AA}/CNM
    - RHIC : σ_{CNMabs} = 1mb
    - SPS : σ_{CNMabs} = 4.18mb
  - $\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$
- Cautions
  - τ_0= 1fm/c too much for RHIC?
  - CNM contribution at RHIC energy badly constrained!



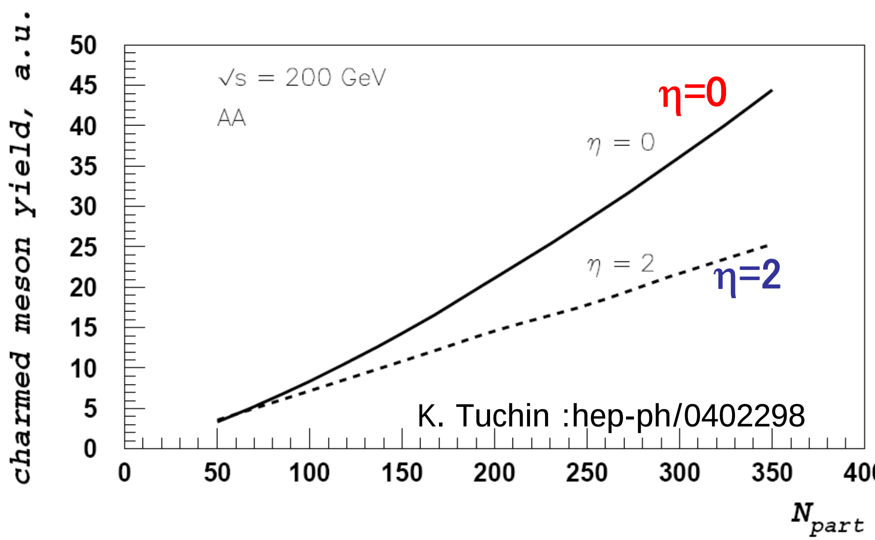
(*) Karsch, Kharzeev, Satz, PLB 637 (2006) 75

More on rapidity dependence of R_{AA}

- Color Glass Condensate
  - Charmed meson calculations based on CGC give higher mid rapidity yields (may not hold for J/ψ)
  - Quantitative prediction for J/ψ in d+Au and Au+Au is indispensable to draw conclusion

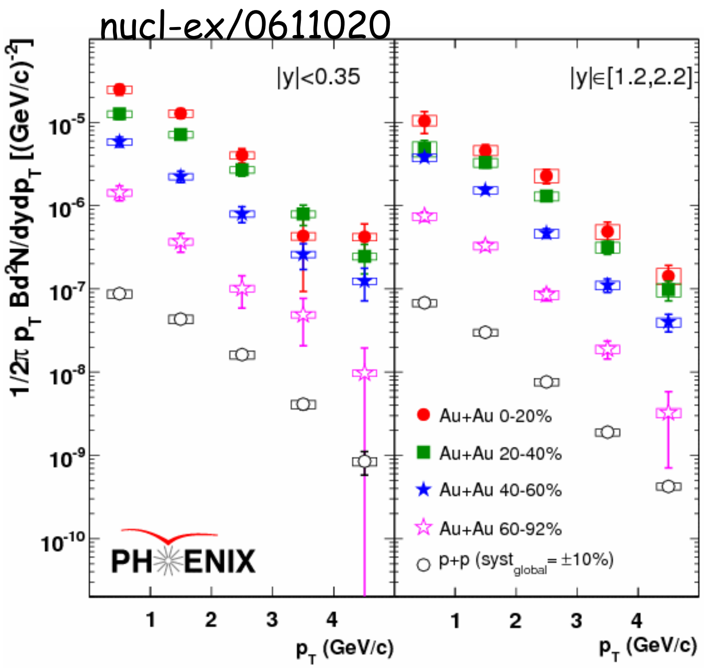


- Regeneration
  - High charm density at RHIC
    - 10 to 20 in most central (*)
  - Recombination at latter stages to populate mid rapidity and low p_T
  - Attenuates the suppression at mid rapidity
  - Testable with p_T hardness

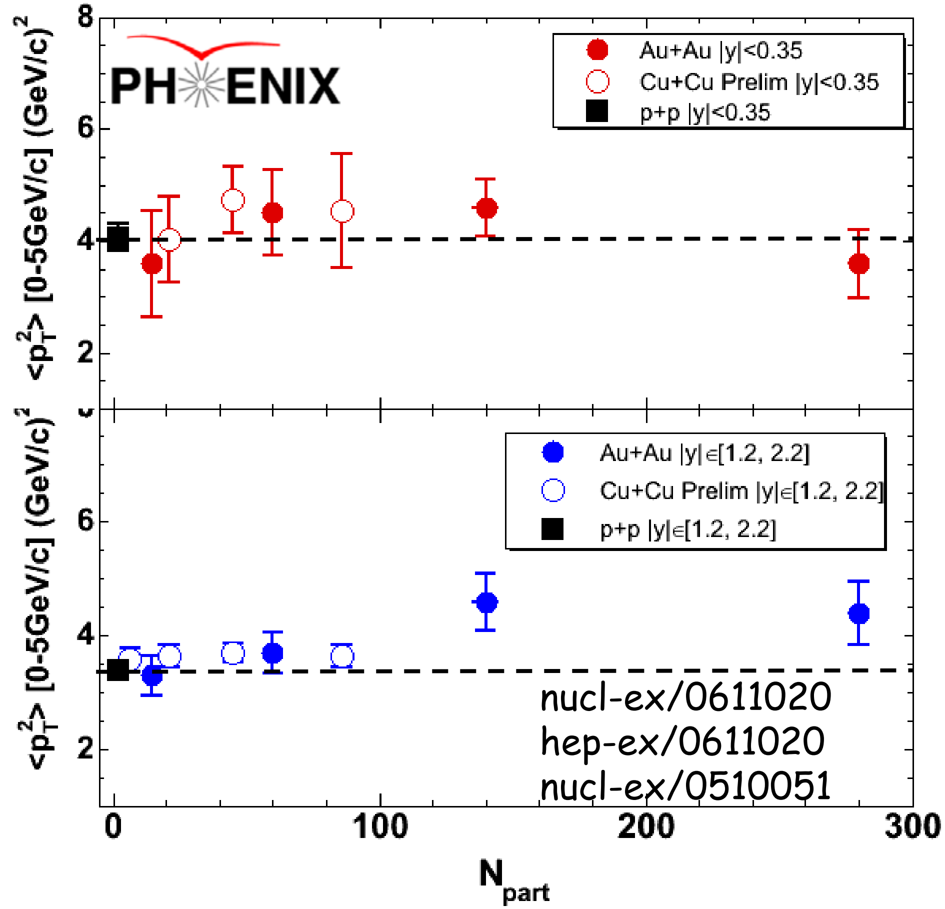


(*) S. S. Adler *et al.* PRL 94 (2005) 082301

Hardness of the p_T spectrum



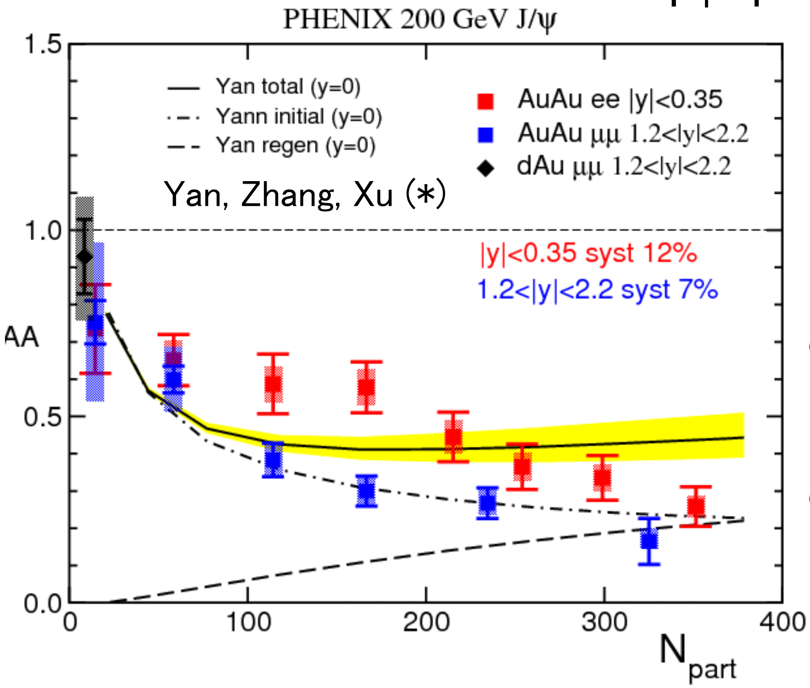
The plotted $\langle p_T^2 \rangle$ is calculated directly from the measured data points (p_T<5GeV/c), no fitting or extrapolation

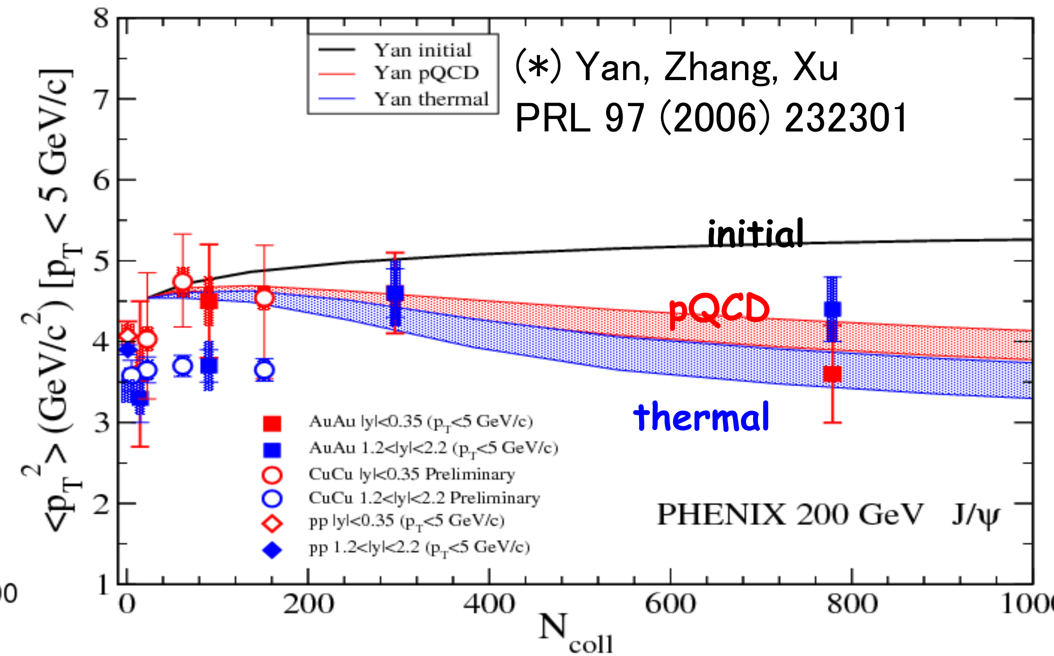


- Hardness of p_T spectrum sensitive to formation mechanism
- No strong N_{part} dependence of $\langle p_T^2 \rangle$, only slight rise at forward rapidity

Testing regeneration models

- Recombined J/ψ populate low p_T
  - This leads to softened p_T spectra and flatten $\langle p_T^2 \rangle$ vs. N_{coll}





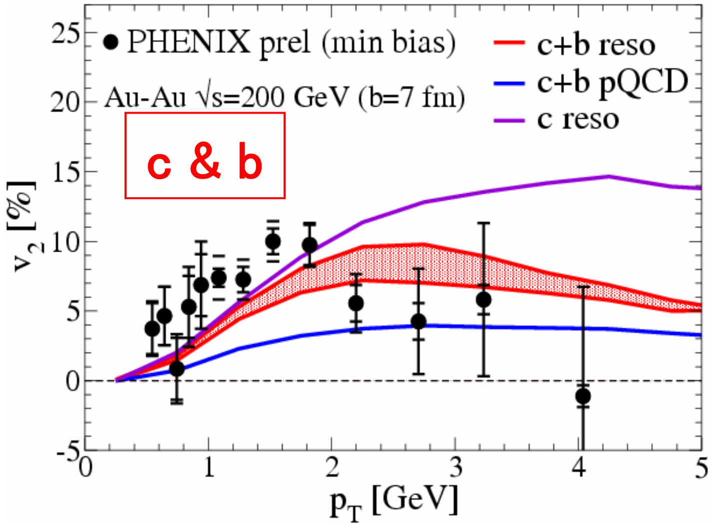
- Detailed knowledge of charm quark production is required to better constrain models.
  - Silicon vertex detector upgrade, being constructed, installation ~ run 9/10

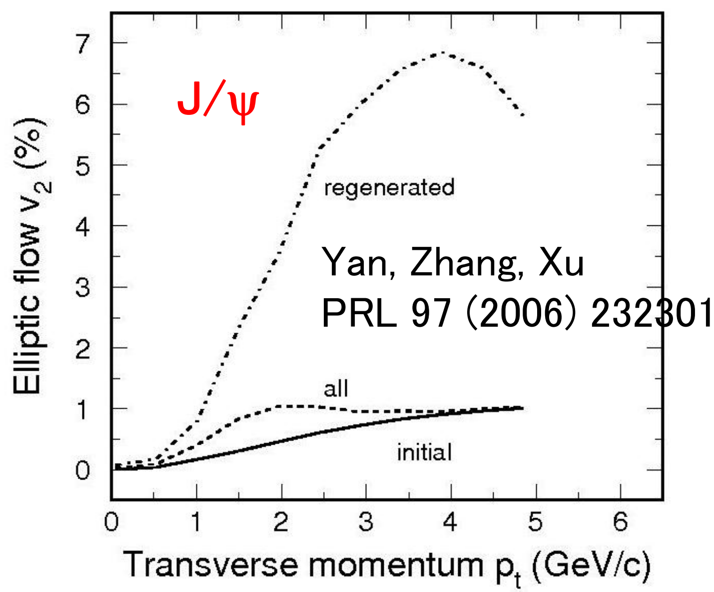
(cf. Talk by J. Lajoie)

Prospects

- J/ψ flow : promising test of regeneration
  - Elliptic flow: collective phenomenon, transforms initial spatial anisotropy of collision region into momentum anisotropy
  - Electrons from c and b quark meson decays have been observed with nonzero elliptic flow

    (cf. Talk by D. Hornback)
  - If regeneration takes place, J/ψ elliptic flow should show similar trend
- New Au+Au run underway
  - ~4x higher statistics expected
  - Upgrade for better reaction plane measurement resolution



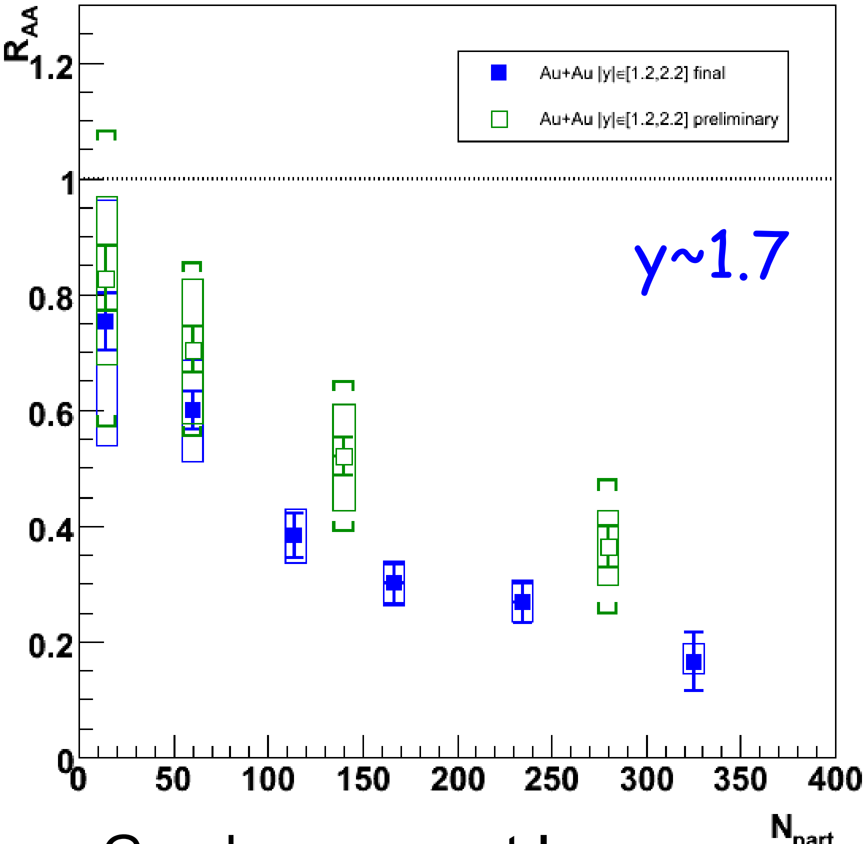


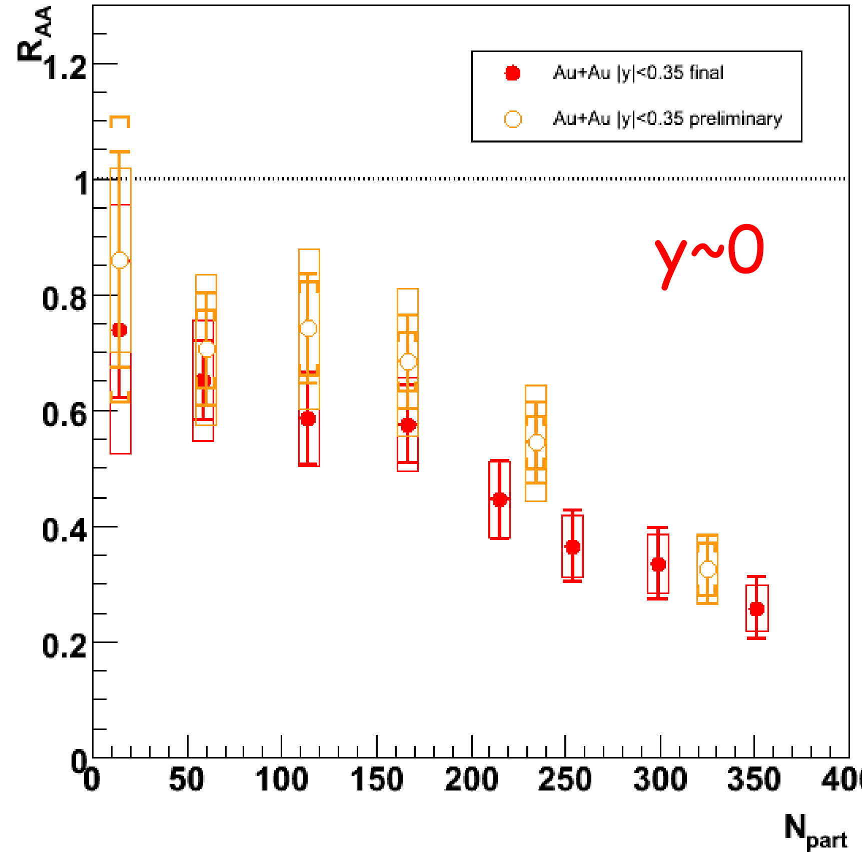
Summary

- Reviewed J/ψ results from PHENIX
  - In p+p collisions, production baseline is measured:
    - The absolute cross sections are compatible with PYTHIA
    - No model explains simultaneously polarization & rapidity distribution
  - In d+Au collisions, cold nuclear matter effects are characterized. Despite lack of statistics, data favors:
    - *Some gluon shadowing and slight nuclear absorption*
    - Much bigger statistics is needed to disentangle CNM effects!
  - In Au+Au measurements:
    - *Very similar suppression at mid rapidity in Au+Au as at SPS*
    - Higher suppression at forward rapidity than at mid rapidity
    - Hardness of pT spectrum is not very sensitive to N_{coll}
  - In Cu+Cu (prelim.), early to draw strong conclusions, final results soon!
- Future runs (higher statistics and upgrades) should help clarify further the global vision.

Backup

QM06 versus QM05



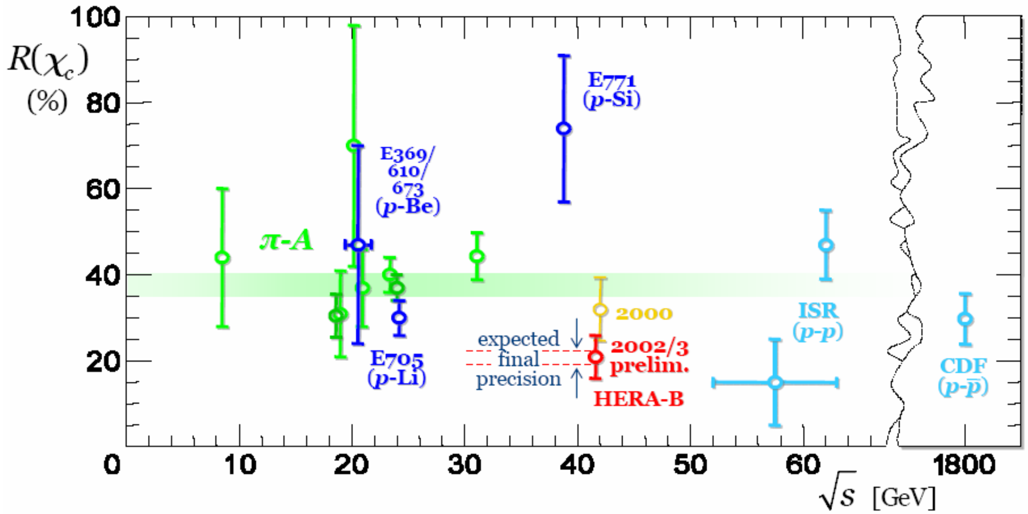


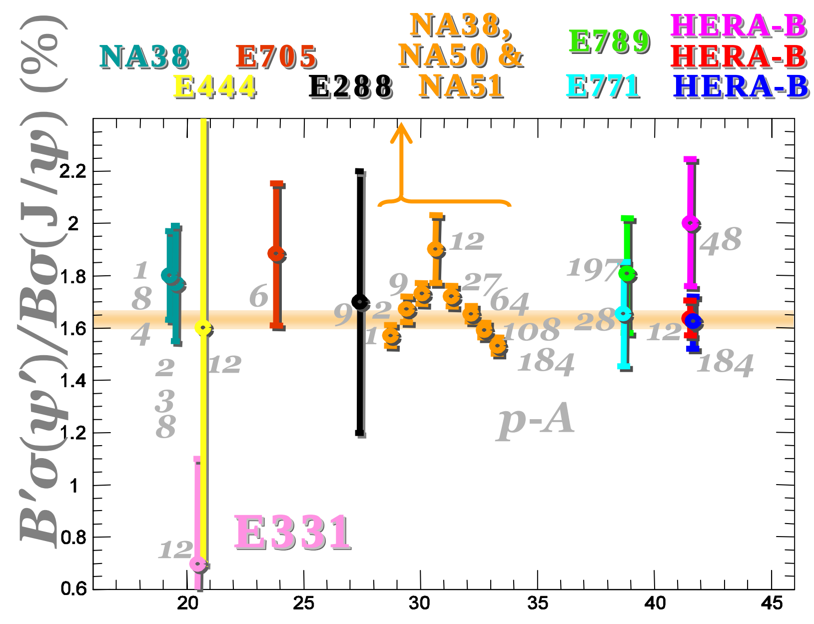
Good agreement !

- At forward rapidity, on the lower edge of systematics
  - (better handling of backgrounds and new pp reference)
- At midrapidity, less <u>subjective</u> "onset" like shape…

Feed down ratios

- From HERA-B (pA $\sqrt{s}$=41.6 GeV)
  - 7.0 ± 0.4 % from ψ'
  - 21 ± 5 % from χ_c
  - 0.065 ± 0.011 % from B





Faccioli, Hard Probes 2006